Validating Mission Relevance of Autonomy Technologies through Increased Science Return

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Abstract

The focus of this paper is to present a methodology for validating the relevance of autonomy technologies to current and future space missions. In this paper, we will discuss the objectives of NASA space exploration missions and explain the requirements needed for autonomy technology to achieve mission goals. By focusing on the underlying purpose of the mission, that of maximizing scientific yield, we will analyze how autonomy technologies address achievement of mission objectives. We will discuss how technologies such as reasoning, planning, and autonomous control, have a direct influence on mission success. The methodology proposed breaks down mission components into operational functions, and discusses how technologies, based on performance metrics, enable achievement of these functions and increases in science return. Specific examples of validating autonomy technologies applied to surface exploration missions will be provided.

1. Introduction

The process of infusing autonomy technologies into future space exploration missions is a daunting task. In most cases, missions justify the inclusion of new technology by determining the effect a given technology has on the utility of the mission, which is computed by combining the utility of outcome with the probability of achieving the outcome [1]. The outcome of a mission depends on the mission objectives and can range from traversal of a rover over a given terrain to imaging a distant star. Risk models are used to estimate the probability of success by evaluating whether the technology can meet mission goals in sufficient time. Typically, these probability factors are computed from extensive experimental, and field data, in which performance failure rates are collected from implementing the algorithm on analogous hardware systems. Maximizing the utility function then enables the creation of a ranking criterion for selection of technologies. For autonomy technologies, especially at low Technology Readiness Levels (TRL), this evaluation process is not always sufficient to understand the benefits of infusing autonomy into the mission scenario. Typically, extensive terrestrial experiment data, or field data, implemented on analogous hardware systems is not always available. Probability factors for assessing failure rates may be qualitative, versus quantitative. And other factors, which relate autonomy technologies directly to increased mission return, such as science density and mission survivability, are not usually classified as tangible mission objectives.

The primary purpose of a surface exploration mission is to enable science return [2]. In fact, the Space Science Enterprise, which is responsible for all of NASA's programs relating to the solar system, strategizes investment in research efforts that can "maximize the scientific yield from our current missions" [3]. An autonomy technology can therefore be linked to achievement of mission goals by evaluating the impact it has on science return. The concept of science return though is a difficult value to measure. Naively, we can say that a technology that increases the quantity of measurements provided by a mission also increases science return. Continuing in this vein, we can say that a technology that increases the success probability of increasing the quantity of measurements increases science return. Theoretically, this process flow can continue on indefinitely. To this effect, a framework must be constructed that systematically relates technologies to science return in a structured fashion. This will enable development of a methodology that allows autonomy technologies to quantify the scientific benefit they bring to the mission, thus providing a means to validate to mission designers the need to embed autonomy technology directly into mission scenarios.

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

2. Mission Operational Functions

The first stage required to validate the relevance of autonomy technologies to current and future space missions is to decompose mission scenarios into operational functions. The integration of technology into NASA exploration missions can occur at three distinct operational levels: on-Earth, in-Space, and/or at-Surface. These operational opportunities are interlinked to enable the mission to target the best sites for detailed measurements and increased science return. As an example, Figure 1 summarizes the operational steps for the Mars surface exploration mission strategy [4].

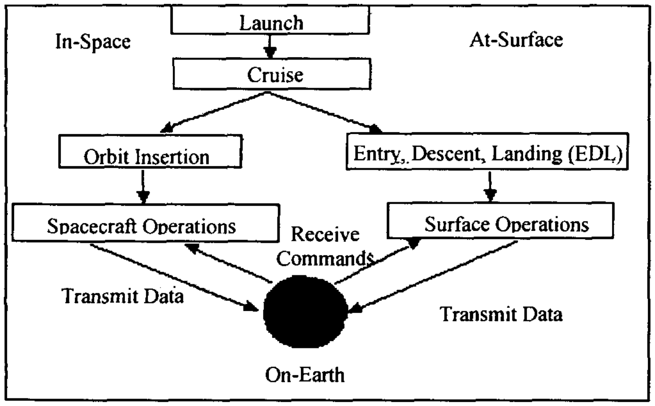

Figure 1: Operational stages for exploring Mars

The mission operational functions can further be subdivided into functional sequences and functional sequences into functional steps. For example, in the upcoming Mars Exploration Mission (MER), surface operations can be separated into the three functional sequences: Mobility, Approach/Instrument Placement, and Sample Handling [5]. Subsequently, functional steps for Mobility include actions such as *Acquire panorama image, locate scientific site of interest, Plan path toward goal,* etc.

Through operational functions, missions are designed to achieve a given set of science goals, where science return is evaluated based on the number of high priority measurements achieved by the mission [6]. To enable science return, technologies must directly address at least one of four components: *science productivity, failures, risk,* and/or *communication efficiency.* Science productivity directly deals with the quality, quantity, and prioritization of the science measurements. Reducing failures ensures that the mission can consistently realize the science measurements by successfully performing necessary operations. Minimizing risk enables the mission to develop the techniques required to perform science, as well as ensure continuous operation of the mission. Communication efficiency ensures that the science product, whether measurements or conclusions, can effectively be conveyed back to Earth. Based on this concept, the value of a technology is assessed by determining how a technology impacts each of the four science return components.

3. Technology Hierarchy

To successfully achieve mission objectives, integration of technology can occur at different levels in the mission scenario. A technology that performs on-board resource planning to extend mission life effects science return, just as a technology that reduces the data dimensionality of science measurements transmitted to Earth. As such, a hierarchy that categorizes the technology in relation to the science return components must first be constructed, such as shown in Figure 2.

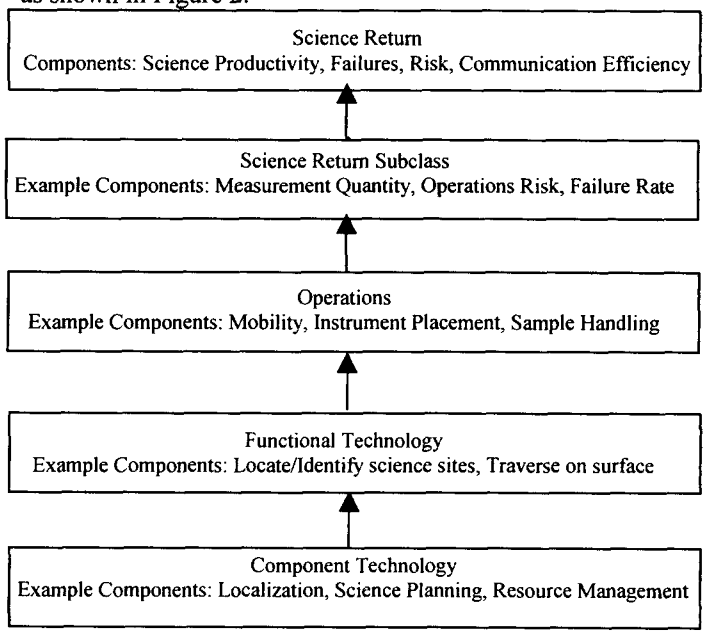

Figure 2. Hierarchy linking autonomy technologies to science return

At the highest level are the four science return components. Each component has subclasses that describe the factors which effect performance of the component. Examples of subclass components are *quantity of measurements* (under the *science productivity* component) and *impact of failure* (under the *failure* component). Below the subclass level is operations, which represents the functional sequences associated with an operational function of the mission. At the next level are technologies that execute steps associated with a functional sequence. The last level in the hierarchy is the component level. Resident at this level are technologies that enable achievement of the functional steps. Example technologies at this level include: localization techniques, opportunistic science planning, and on-board resource management.

4. Technology Impact on Science Return

Performance metrics are defined to capture important attributes of each technology, as relates to its associated technology level. The performance metrics are characteristics of how the technology impacts the technology level. For example, a *mobility* technology, which is resident at the functional level, has performance metrics that relate to distance traveled per sol, whereas a *localization* technology, which is located at the component level, has performance metrics that relates accuracy to distance traveled.

Although a technology may belong to the same technology level (e.g. component, functional, etc.), it may relate to different components at that level. Thus, a technology's performance parameters may differ from other technologies in the same level. For example, a performance metric for a *science planning* technology (resident at the component level) is related to science sites. On the other hand, the performance metric for a *localization* technology (also resident at the component level) is related to accuracy. Although these two technologies address different functional steps, they belong to the same technology level. In order to enable multiattribute validation and ultimately understand the impact of technologies on the mission, performance parameters must be normalized into a unitless measure. Technology impact is therefore calculated based on normalizing the difference between technology performance and the performance of current baseline State-of-the-Art (SOA) technology, such that:

$$\text{Technology Impact Score} = \frac{1}{w}\frac{\sum \tau_c - \beta_c}{\tau_c}$$

where w is the number of performance metrics available for assessing the component, β_c is the SOA capability with respect to the performance metric, and τ_c is the capability of the technology with respect to the performance metric. This difference value is summed over all performance metrics common to the technology. Once calculated, the Technology Impact Score (*TIS*) for that level is then determined such that:

$$\text{Technology Level Impact Score } (n) = \frac{1}{w_n} \Sigma \, TIS$$

where n represents the technology level in the hierarchy, w_n is the number of components resident at that level, and the value is summed over all components resident at the n^{th} level. To propagate the Technology Impact Score up the hierarchy, Technology Impact Scores for each component are determined and used to determine the Technology Level Impact Score for the next level.

$$\text{Technology Impact Score } (C_i, N) = \frac{1}{w_i} \Sigma \, TIS\,(\text{i, N-1})$$

$$\text{Technology Level Impact Score } (N) = \frac{1}{w_N} \Sigma \, TIS\,(C_i, N)$$

where N is the next level in the hierarchy, C_i are the components resident at level N, w_i is the impact weight of component i divided by the number of related components from the previous level. The Technology Impact Score is summed over all components at the $(\text{N-1})^{\text{th}}$ level that are linked to component i at level N. The Technology Level Impact Score is then computed by summing over all Technology Impact Scores for components resident at the N^{th} level. Since the highest level of the hierarchy includes the science return components, the Technology Impact Scores calculated at the final level represents the technology impact on science return.

5. Validating Autonomy Technologies for Surface Exploration Missions

As an example, we selected two autonomy technologies, reconfigurable robots [7] and terrain-based navigation [8], to determine their impact on future Mars surface exploration missions. We began by constructing an in-depth analysis of the functional steps, sequences, and operations for Mars surface exploration missions. We then collected performance metrics for the two tasks and propagated the Technology Impact Score calculated at the functional level to determine impact on science return. The objective of the reconfigurable robotic technology is to combine autonomous learning and software reconfiguration with modular hardware components to construct small, fault-tolerant robotic vehicles. As relates to the four science return components, the performance characteristics of this task increases science productivity and reduces failures. Terrain-based navigation involves incorporating perception-based terrain assessment and soft computing techniques for navigation on rough terrain. This task improves science productivity, increases communication efficiency, and reduces risk associated with surface operations. The following table shows a subset of the assessment process for the two tasks. From this analysis, we conclude that reconfigurable robotic technology has a larger impact on science return than terrain-based navigation. Intuitively, this makes sense

Terrain-Based Navigation Technology		Performance Metric	SOA	Technology
		Terrain complexity (traversability/m^2)	0.2	0.9
Component Level	**Component Description**	Number of surface points (number/sol)	2	5
Functional	Enable traverse to diverse set of surface points, on Mars surface between points > 5 km	Technology Impact Score		0.4100
	Science Return	Technology Impact on Science Return		0.0051

Reconfigurable Robotic Technology		Performance Metric	SOA	Technology
		Effective Speed (cm/sec)	0.2	5
Component Level	**Component Description**	Number of surface points (number/sol)	2	20
Functional	Enable traverse to diverse set of surface points, on Mars surface between points > 5 km	Technology Impact Score		0.9300
	Science Return	Technology Impact on Science Return		0.0087

since reconfiguration is typically a high-risk, high-return technology as applied in most areas.

6. Conclusion

In this paper, we have presented a methodology for validating the relevance of autonomy technologies to current and future space missions. The objective of NASA space exploration missions is quantified in terms of science return, and achievement of those objectives is represented as a set of mission operational functions. Technologies are then linked to the mission through a hierarchy that associates performance metrics directly to science return. The methodology presented allows a means to validate the need for autonomy technology by developing a structured approach for assessment. Future work will involve analyzing the benefit of currently funded autonomy technologies as applied to future Mars missions.

7. References

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